DOMINANT ROLE OF THE EXPLOSIVELY EXPANDING ARMATURE ON THE INITIATION OF ELECTRIC DISCHARGE IN MAGNETIC FLUX COMPRESSION GENERATORS

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Abstract

Electric discharge within the magnetic flux compression generator (FCG) is one of the energy losses mechanisms in the system. In this paper, we experimentally demonstrate that the explosively expanding armature of the FCG plays a dominant role in the formation of plasma and initiation of electric discharge inside the FCG.

I. INTRODUCTION

In explosive pulsed power systems, the initial energy is provided by explosive materials [1]. This makes explosive pulsed power devices fundamentally different from conventional pulsed power systems powered from 110V/50Hz supply lines or electrochemical cells. Explosively driven magnetic flux compression generators [1], ferromagnetic generators [2,3], ferroelectric generators [4,5] and moving magnet generators [6,7] convert the chemical energy of high explosives into pulses of high electrical current, high voltage and high power. Low and high explosive materials, detonation waves, shock waves, high pressure gases, explosive destruction and other related effects are inalienable parts of the operation of these devices [1-7].

The magnetic flux compression generators are powerful explosive pulsed power systems that are capable of producing output pulses of electromagnetic energy up to tens of megajoules [1]. Initiation of electric discharges in helical FCGs was reported earlier [8,9]. It was demonstrated that magnetic flux loss in FCGs increases to about 50% due to electric discharge [8].

There are several mechanisms of the initiation of electric discharge in gases in conventional pulsed power systems [10]. Metallic electrodes play an important role in the process of the initiation of the gas discharge providing free electrons in the gas gap due to the secondary electron emission, photoelectron emission, or field electron emission. But the main factor that effects the probability of ionization of the gas and the formation of plasma is the electric field strength in the system [10]. An increase of the electric field strength in the device above a threshold level results in the immediate initiation of the gas discharge.

Recently we experimentally demonstrated that the main factor that causes the initiation of the gas discharge in the FCG is not the electric field strength within the generator, but the explosive expansion of the armature that plays a dominant role in the formation of plasma and gas discharge initiation [11]. In this paper we present extended results of these studies. In addition, we experimentally demonstrate that an explosively expanding metallic surface can cause gas ionization and the formation of plasma in a system with no other electric fields.

II. RESULTS AND DISCUSSION

We performed experimental studies of FCGs with simultaneous recording of pulsed signals produced by the generators and high-speed photography of its operation. The studies provided detailed information about the development of electric discharges during different stages of the operation of FCGs.

Experiments were conducted with the loop magnetic flux compression generator (LFCG) [12]. The explosive and electrical operation of a loop FCG is similar to other types of FCGs (i.e. coaxial FCG and helical FCG), because of magnetic flux compression inside the stator due to the expansion of a cylindrical armature loaded along its major axis with a high explosive charge [1]. The specific feature of an LFCG is the opportunity to observe in detail the processes that occur inside the generator (expansion of the armature, closing the crowbar contacts, etc.) from the very beginning until the final stage of its operation, something that cannot be done when studying helical, coaxial or other types of flux compression generators. Results obtained with the miniature LFCG we developed for these studies can be used to better understand the initiation of electrical discharges in LFCGs of larger sizes, and in helical and coaxial FCGs.

A schematic diagram of the experimental setup is in Fig. 1. We performed high-speed photography of the LFCG operation with a Cordin 10A framing camera. To avoid any shock-induced glow in the atmosphere around the LFCG during its operation, we put the generator in a disposable wooden box that we purged with helium immediately before firing a shot. A 10-tube flash array (also disposable) was installed in the box to provide sufficient illumination to expose the camera film, and the

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14. ABSTRACT
Electric discharge within the magnetic flux compression generator (FCG) is one of the energy losses mechanisms in the system. In this paper, we experimentally demonstrate that the explosively expanding armature of the FCG plays a dominant role in the formation of plasma and initiation of electric discharge inside the FCG.

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box inner surfaces were coated with a white finish to evenly distribute the illumination. The array was charged to 780 V and was forced to discharge by a high voltage signal passed to a trigger wire that surrounded each flash tube.
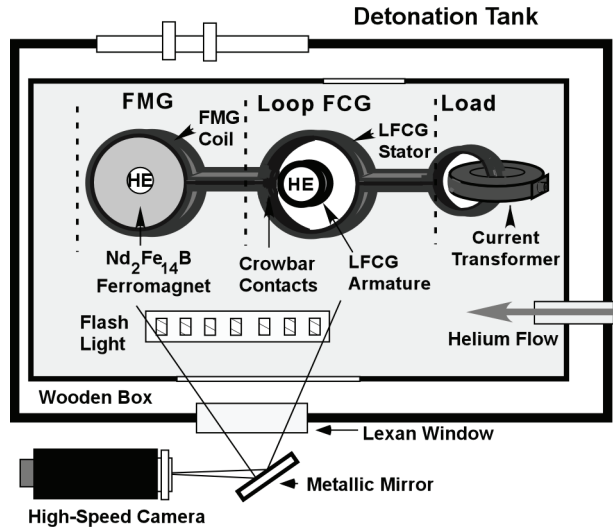

Figure 1. A schematic diagram of the experimental setup for studies FCGs with simultaneous recording of pulsed signals produced by the generators and high-speed photography of its operation.

The basis for the operation of a flux compression generator is the expansion of its armature upon the detonation of a high explosives (HE) charge, compression of an initial magnetic field trapped in its stator, and the resulting amplification of current and energy in the load [1]. The initial magnetic flux, Φ_0, and the initial magnetic energy, W_0, are important parameters of the system. As a rule, Φ_0 and W_0 in the FCG are created with an electrical current (seed current, I_{seed}) that is generated by discharging a capacitor bank that has been charged by a conventional power supply. To avoid the effect of external electric circuits and external electric potentials on the initiation and development of the electric discharge in the LFCG, we decided not to use a conventional capacitor bank-based system to power the LFCG. To generate I_{seed} in the LFCG, we utilized a recently invented [2,3] autonomous explosively driven primary power source, the shock-wave ferromagnetic generator (FMG), which is based on the effect of transverse shock wave demagnetization of $Nd_2Fe_{14}B$ high-energy hard ferromagnets. The FMG-LFCG pulsed power systems that we studied were completely autonomous, being powered exclusively by high explosives with no external electrical circuits or power supplies except for those required for the detonators.

The inner diameter of the LFCG stator was 50.0 mm (Fig. 1). The stator was made of a bare copper strip, 13.0 mm wide and 1.0 mm thick. The cylindrical armature of the LFCG was made of 6061 aluminum alloy tubing of

O.D. = 25.4 mm, I.D. = 22.4 mm and h = 37.5 mm. The length of the HE charge loaded in the armature of the LFCG was 19.0 mm (10.2 g of desensitized RDX) with two 1.0 mm thick metallic rings and two RP-80 detonators, attached one at each end of the charge.

The FMG-LFCG-Load system charged with high explosives, and placed in a wooden box right before the installation in the detonation tank is in Fig. 2.
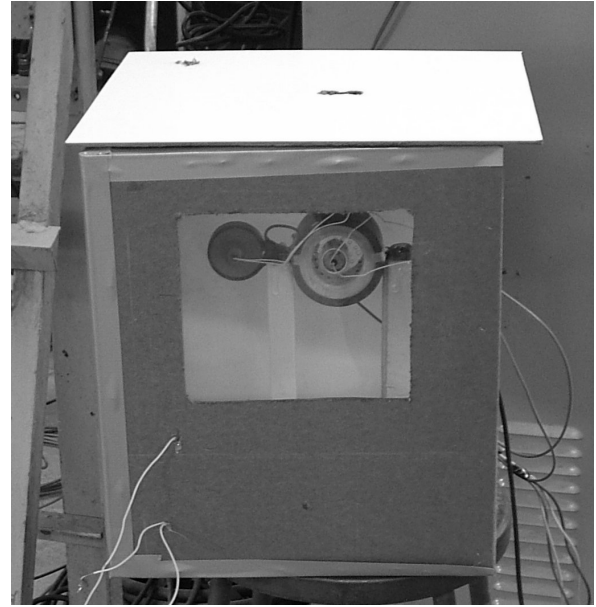

Figure 2. The FMG-LFCG system prepared for high-speed photography.

Figure 3 presents a series of high-speed photographs (1/2 million frames per second) of the explosive operations of the FMG-LFCG system. Figure 3 shows the corresponding waveform of the current pulse produced by the FMG-LFCG system, along with the seed current waveform and the FMG output voltage waveform. The waveforms in Fig. 4 are marked with letters that correspond to the letters marking the photos in Fig. 3. In the photographs shown in Fig. 3, the FMG is on the left and the LFCG is on the right. All parts of the FMG-LFCG system are captioned in Fig. 3(A).

At t = 0 µs, the detonators of the FMG seed source were initiated [Fig. 3(A)] and the HE charge (0.7 g of C-4) loaded in central hole of the $Nd_2Fe_{14}B$ hard ferromagnetic ring was detonated. A bright light is clearly visible in the central hole of the $Nd_2Fe_{14}B$ ferromagnet [Fig. 3(B)] due to the initiation of the HE charge. This process of initiation of HE materials is well-studied (see refs. in [1]). The HE charge was in direct contact with the $Nd_2Fe_{14}B$; as such, the transverse shock wave from the explosives detonation propagated through the body of the $Nd_2Fe_{14}B$ ring from its central hole to its periphery. Due to the transverse shock demagnetization of the $Nd_2Fe_{14}B$, the FMG seed source produced a pulsed voltage at the input of the LFCG (across the contacts of the crowbar). The

voltage reached its peak amplitude at $t = 10$ μs [Figs. 3(F) and 4], and $U_{crowbar}(10$ μs$) = 35.4$ V. The voltage pulse caused an increasing seed current in the FMG-LFCG-Load system (Fig. 4). The seed current reached its maximum, 2.6 kA, at $t = 28$ μs [Figs. 3(K) and 4.

The inductance of the LFCG and the load in these experiments were $L_{LFCG}(100$ KHz$) = 67\pm7$ nH and $L_{Load}(100$ KHz$) = 62\pm7$ nH, respectively. At $t = 28$ μs, the magnetic flux and the energy produced by the FMG in the LFCG-Load system reached maxima of $\Phi_0(28$ μs$)_{max} = 353$ μWb, and $W_0(28$ μs$)_{max} = 460$ mJ, respectively.

The detonators of the LFCG were initiated with a delay of $t_d = 24$ μs after the initiation of those in the FMG. In Fig. 3(I), one can see the light due to the detonation of the HE inside the armature of the LFCG. The denotation wave moved through the HE charge inside the aluminum armature for a period of 1.2 μs. It took 0.2 μs for the shock-wave front to pass through the walls of the armature, after which it entered into the gas (helium in this case) in the surrounding space. The shock-wave front propagated through the gap between the armature and the crowbars of the LFCG for 3.2 μs and then reached the stator.
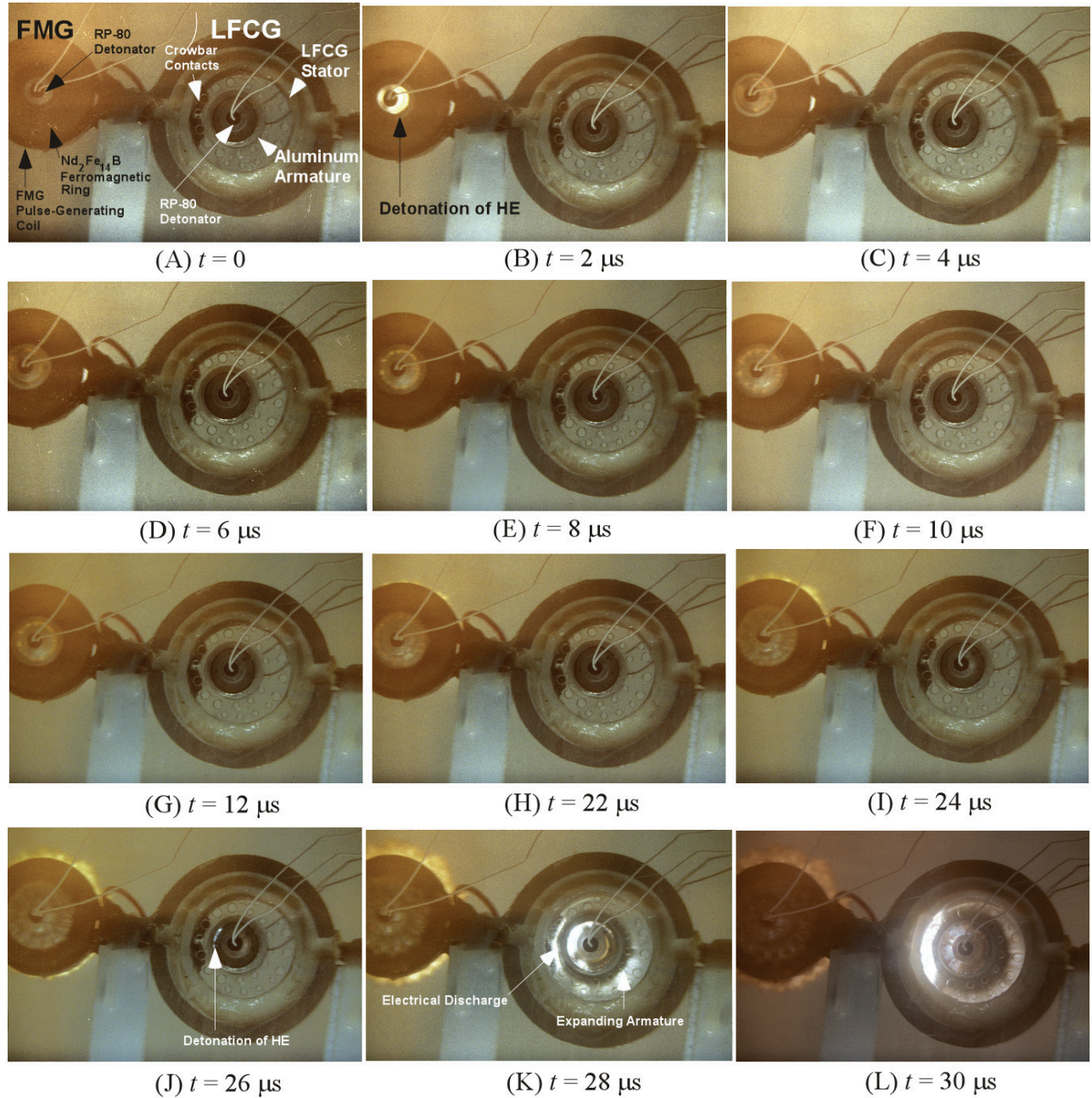

(A) $t = 0$ (B) $t = 2$ μs   (C) $t = 4$ μs

(D) $t = 6$ μs   (E) $t = 8$ μs   (F) $t = 10$ μs

(G) $t = 12$ μs   (H) $t = 22$ μs   (I) $t = 24$ μs

(J) $t = 26$ μs   (K) $t = 28$ μs   (L) $t = 30$ μs

Figure 3. A series of high-speed photographs taken during explosive and electrical operation of FMG-LFCG-Load system.

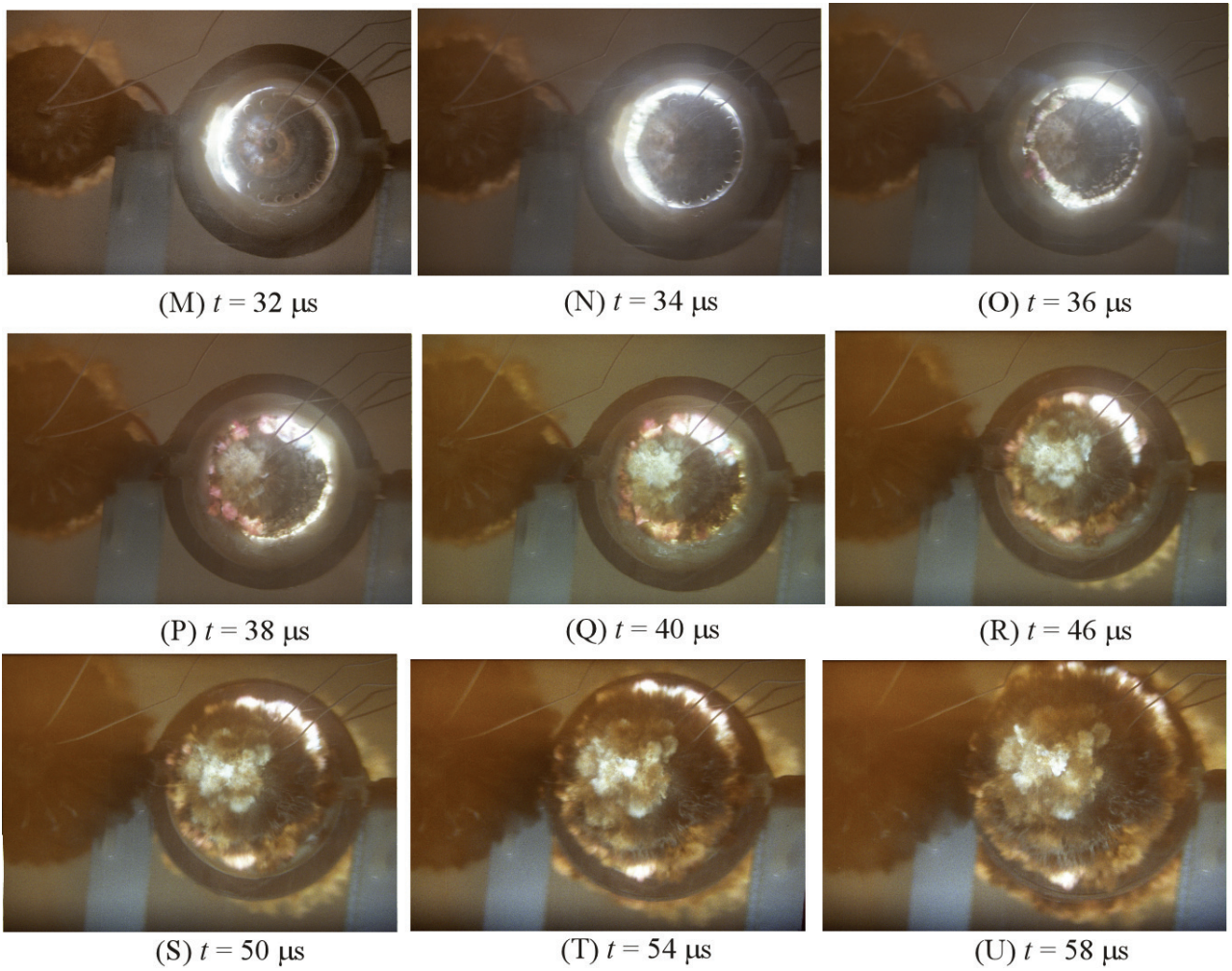| (M) $t = 32$ μs | (N) $t = 34$ μs | (O) $t = 36$ μs |
| (P) $t = 38$ μs | (Q) $t = 40$ μs | (R) $t = 46$ μs |
| (S) $t = 50$ μs | (T) $t = 54$ μs | (U) $t = 58$ μs |

Figure 3 (continued). A series of high-speed photographs taken during explosive and electrical operation of FMG-LFCG-Load system.

Due to the action of the shock wave and high pressure gases from the detonation of HE charge inside the aluminum armature of the LFCG, the armature started its expansion (the expanding armature is the dark contour in the photographs [Figs. 3(K),(L),(M)]).

Exactly at the moment when the armature started its expansion, plasma appeared in the gap between the armature and the crowbar and in the gap between the contacts of the crowbar [Fig. 3(K) ($t = 28$ μs)]. The voltage between the crowbar contacts (two copper cylinders of diameter 10 mm, length 5 mm, edge radius 1.5 mm, with a 2.5 mm gap between them) was very low, $U_{crowbar}(28$ μs$) = 3.6$ V (Fig. 4) and the corresponding electric field strength is estimated to be $E_{crowbar}(28$ μs$) = 0.07$ kV/cm. The electric field was definitely not high enough to initiate an electric discharge in helium [10]. Therefore, the initiation and development of the electric discharge in the LFCG as seen in Figure 3 cannot be directly related to high electric fields in the system.

Direct evidence of the critical role of the explosively expanding armature in the formation of plasma and initiation of the electric discharge in the FCG is the fact that the discharge at the crowbar was not initiated at $t = 10$ μs [Figs. 3(F) and 4], when the armature did not expand. The voltage across the contacts of the crowbar at that time was almost an order of magnitude higher than that at $t = 28$ μs, $U_{crowbar}(10$ μs$) = 35.4$ V (Fig. 4) and the corresponding electric field strength is estimated to be $E_{crowbar}(10$ μs$) = 0.7$ kV/cm.

At $t = 30$ μs [Figs. 3(L) and 4], the expanding armature made contact with the crowbar and closed it. At this moment, the FMG seed source was disconnected from the FCG-Load circuit and magnetic flux was trapped in the LFCG between the stator and expanding armature. A bright light appeared at the contact point between the armature and the crowbar [Fig. 3(L)] due to plasma arising from the intense electric discharge that occurred when the armature approached the crowbar and made contact.
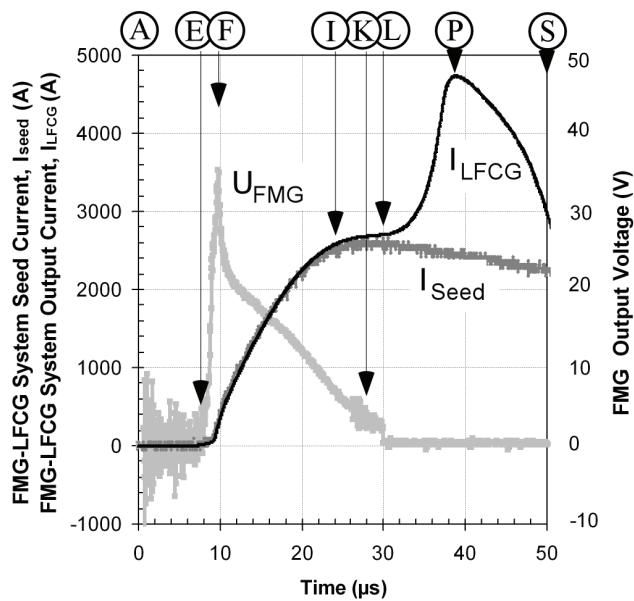
Figure 4. Waveforms of the output voltage pulse (light gray) and seed current pulse (dark gray) produced by the FMG seed source in the LFCG-Load system, and the waveform of the current pulse produced by the completely explosive FMG-LFCG-Load system (black) corresponding to the high-speed photographs shown in Fig. 3.

After t = 30 μs, further expansion of the armature led to the compression of the magnetic field in the space between the armature and the stator of the LFCG, resulting in amplification of the current in the load (Fig. 4). The expansion of the armature was accompanied by the generation of a plasma that filled the gap between the armature and the stator [Fig. 3(M),(N),(O)].

The contact point between the armature and the stator was not just a short-circuit connection between two metallic contacts; instead, it was a triple point containing plasma, the armature, and the stator. Thus, the electrical resistance of armature-stator contact point depended on the properties of the plasma generated by the expanding armature. Therefore, the creation of plasma at the armature-stator contact is a possible cause of energy losses in the FCG.

At t = 38 μs, an intense plasma was distributed along the entire perimeter of the stator, including the output terminals of the LFCG [Fig. 3(P)]. Apparently, this plasma short-circuited the output terminals of the LFCG at that point and shut off the continued increase in the output current, which reached is peak amplitude value at t = 38 μs, I_{max}(38 μs) = 4730 A (Fig. 4). Despite the miniature dimensions of the LFCG, the current amplification and energy compression coefficients of the FMG-LFCG system (Fig. 1) are comparable with those obtained with large-scale high-power LFCGs [12].

At t = 46 μs, mechanical destruction of the LFCG is clearly seen [Fig. 3(R)]. At t = 58 μs, The FMG-LFCG system is complete destroyed [Fig. 3(U)].

Apparently, the formation of plasma and initiation of the electrical discharge within the stator of the LFCG is the result of two different shock processes in the gas between the stator of the LFCG and the expanding armature. The first shock process results from the detonation of the HE inside the armature. Passage of this detonation shock through the LFCG compresses, heats and excites the gas within the flux compressor [13].

After the detonation shock front propagates through the gas, the armature begins its expansion (see timing above). Based on high-speed photograph images, the speed of the expansion is 1.6±0.1 mm/μs at the initial stage of the expansion and 2.9±0.1 mm/μs at the final stage. This is nearly three times faster than the normal acoustic velocity of the gas fill; therefore, gas in the path of this expansion forms a shock in the same manner that a supersonic aircraft forms an air shock (so-called "breaking the sound barrier"). This shock builds in front of the expanding armature in the gas, re-compressing the already shocked gas. The compression process results in greater heating, and therefore, greater excitation of the gas immediately in front of the expanding armature when compared to the excitation caused only by passage of the detonation shock.

Because of the two shock processes happening in quick succession, a part of the gas is ionized and plasma is formed in the gas between the armature and the stator [13]. The appearance of plasma causes initiation of the electrical discharge in the system, even at very low electric fields.
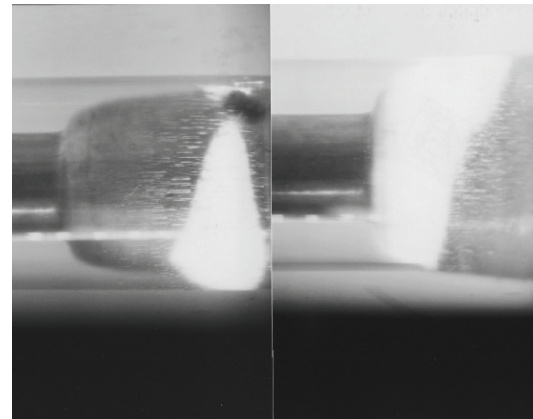

Figure 5. High-speed photographs taken during explosive expansion of a cylindrical metallic armature inside clear polycarbonate tubing.

To prove our results of the dominant role of the explosively expanding armature in the initiation of the gas discharge within the FCG we performed a series of additional experiments. A cylindrical copper armature (O.D.= 38.0 mm) was loaded with an RDX high explosive

charge and placed inside clear polycarbonate tubing (I.D. = 50.8 mm). There was no metallic stator in the system, and there were no pulsed electric and magnetic fields within the polycarbonate tubing. High-speed photographs of the expansion of this armature are shown in Fig. 5. The time interval between photographs in Fig. 5 is 2 μs. One may clearly see quickly expanding plasma forming at the surface of the armature.

III. SUMMARY

We experimentally demonstrated the dominant role of the explosively expanding metallic armature in the formation of plasma and initiation of electric discharge in the FCG. It is obvious that the plasma formation processes observed and described herein take place in helical and coaxial FCGs, too, where cylindrically expanding armatures also cause formation of plasma and initiation of the electrical discharges.

There are no design-independent thresholds for plasma formation and electrical discharge initiation within the FCG. The thresholds will depend on the shape and placement of the conductors and insulators, and on the materials used for each. It is possible to reduce the intensity of the electrical discharge (and the corresponding energy losses in the system) through decreasing the electrical field strength within the FCG by careful control of the crowbar profile and by using electrical insulation coating for the crowbar and the stator of the FCG.

Apparently, the gas ionization and formation of plasma observed in this work also take place in explosively driven ferromagnetic generators [2,3], ferroelectric generators [4,5] and moving magnet generators [6,7], where explosively accelerated metallic surfaces are inalienable parts of the systems.

IV. REFERENCES

[1] L.L. Altgilbers, J. Baird, B. Freeman, C.S. Lynch, and S.I. Shkuratov, Explosive Pulsed Power. Imperial College Press, London, 2009.

[2] S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, and M. Kristiansen, "Compact Explosive-Driven Generator of Primary Power Based on a Longitudinal Shock Wave Demagnetization of Hard Ferri- and Ferromagnets," IEEE Transaction on Plasma Science, vol. 30, No. 5, pp. 1681-1691, 2002.

[3] S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, and M. Kristiansen, "Currents Produced by Explosive Driven Transverse Shock Wave Ferromagnetic Source of Primary Power in a Coaxial Single-Turn Seeding Coil of a Magnetocumulative Generator," J. Appl. Phys., vol. 93, pp. 4529-4535, 2003.

[4] S.I. Shkuratov, E.F. Talantsev, L. Menon, H. Temkin, J. Baird, and L.L. Altgilbers, "Compact high-voltage generator of primary power based on shock wave depolarization of lead zirconate titanate piezoelectric ceramics, " Review of Scientific Instruments, vol. 75, pp. 2766-2769, 2004.

[5] S.I. Shkuratov, J. Baird, E.F. Talantsev, A.V. Ponomarev, L.L. Altgilbers, A.H. Stults, "High voltage charging of a capacitor bank, " IEEE Trans. Plasma Science, vol. 36, pp. 44-51, 2008.

[6] S.I. Shkuratov, M. Kristiansen, J.C. Dickens, L.L. Hatfield, R. Martin, "Pulsed power generation using open and closed ferromagnetic circuits," IEEE Trans. Plasma Science, vol. 28, pp. 1342-1346, 2000.

[7] S.I. Shkuratov, M. Kristiansen, J.C. Dickens, "Explosive-driven moving magnet generators," in Pulsed Power Plasma Science, 2001. PPPS-2001. Digest of Technical Papers, vol. 2, pp. 963-966, 2002.

[8] J.V. Parker, T.C. Cavazos, C.E. Roth, J.H. Degnan, G.F. Kiuttu, F.M. Lehr, S.K. Coffey, "Development and Testing High-Gain Magnetic Flux Compression Generator," in Proceedings of the 2006 Int. Conf. on Megagauss Magnetic Fields and Related Topics, Eds. by G.F. Kiuttu, R.E. Reinovsky, P.J. Turchi (IEEE Catalog Number: CFP06MEG-PRT), 2007, pp. 265-274.

[9] P. Appelgren, G. Bjarnholt, M. Elfsberg, T. Hurtig, A. Larsson, S.E. Nyholm, "Small Helical Magnetic Flux Compression Generators: Experiments and Analysis," in Digest of Technical Papers, 16th IEEE International Pulsed Power Conference, 2007, pp. 1151-1154.

[10] G.A. Mesyats, Pulsed Power. Kluwer Academic/Plenum Publishers, New York, 2005.

[11] S.I. Shkuratov, J. Baird, E.F. Talantsev, and L.L. Altgilbers, "Electric Discharge Caused by Expanding Armatures in Flux Compression Generators," Appl. Phys. Letters, vol. 94, 171502 (2009).

[12] V.A. Vasyukov, "Explosive Magnetic Generators of a Loop Type Operating within a Middle Range of Fast Current Pulses (15-45 MA)," in Megagauss and Megaampere Pulse Technology and Applications, Eds. by V.K. Chernyshev, V.D. Selemir, and L.N. Plyashkevich (VNIIEF Press, Sarov, Russia), 1997, pp. 292-293.

[13] Ya.B. Zel'dovich and Yu.P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena. Dover Publications, New York, 2002.